

Minimum mass of galaxies from BEC or scalar field dark matter

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ABSTRACT: Many problems of cold dark matter models such as the cusp problem and the missing satellite problem can be alleviated, if galactic halo dark matter particles are ultra-light scalar particles and in Bose-Einstein condensate (BEC), thanks to a characteristic length scale of the particles. We show that this finite length scale of the dark matter can also explain the recently observed common central mass of the Milky Way satellites ($\sim 10^7 M_\odot$) independent of their luminosity, if the mass of the dark matter particle is about $10^{-22} eV$.

KEYWORDS: Dark matter, Bose-Einstein condensate, Dwarf galaxies.

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1. Introduction

Dark matter (DM) is one of the most important puzzles in modern physics and cosmology. Since the presence of DM was inferred from gravitational effects on visible matter in galaxies [1], a good DM model should explain the structure and evolution of galaxies. The dwarf galaxies seem to be the smallest dark matter dominated astronomical objects and, hence, are ideal for studying the nature of DM [2]. Observational data suggest that a typical dwarf galaxy has a size never less than $O(10^2)$ pc. This could pose a challenge to the structure formation theory based on a simple cold dark matter (CDM) model [2], because there is no scale that can be easily accessed observationally in the CDM theory. (However, there is surely a scale in the structure formation of baryons in DM halos. Understanding theoretically the scale is a major topic of present-day research.)

Although CDM such as WIMP (Weakly Interacting Massive Particles) with the cosmological constant (Λ CDM) model is popular and remarkably successful in explaining large scale structures of the universe, it seems to encounter many other problems such as the cusp problem and the missing satellite problem on a scale of galactic or sub-galactic structures [3]. For example, numerical studies with the Λ CDM model usually predict a diverging central halo DM density $\rho_{DM}(r) \propto 1/r^\alpha$, $\alpha \gtrsim 1$, where r is a distance from the center of a galaxy, while observations indicate that some low surface brightness galaxies have an almost flat core density. (However, some dwarf spheroidal satellites of the Milky Way have steeper DM density profiles.) The CDM theory also predicts many satellite galaxies ($O(10^3)$) around the Milky Way, however, only $O(10^2)$ satellite galaxies are observed at most [4, 5, 6, 7].

Recently, it was also found that the mass enclosed within a radius of 300 pc in these galaxies is approximately constant ($\sim 10^7 M_\odot$) regardless of their luminosity between 10^3 and $10^7 L_\odot$ [8]. This result implies the existence of a minimum mass scale for the dwarf galaxies [9, 2] independent of their baryon matter fraction, in addition to the minimum

length scale. This observational fact could be also problematic with the Λ CDM model, which usually predicts many dark matter dominated structures smaller than the dwarf galaxies down to $10^{-6}M_{\odot}$ [10]. (Strigari et al [8] suggested that this difficulty can be overcome if we consider roles of baryonic matter.)

In this paper, we suggest that a cold dark matter model based on Bose-Einstein condensate (BEC) [11] or scalar field dark matter (SFDM) [12] can explain this minimum mass as well as the minimum length scale observed. Considering observational and theoretical uncertainties, we are here concerned with the scales correct within an order of magnitude.

Let us briefly review the history of the DM theory based on BEC. In 1992, to explain the observed galactic rotation curves, Sin [11, 13] suggested that galactic halos are astronomical objects in BEC of ultra-light (with mass $m \simeq O(10^{-24})eV$) DM particles such as pseudo Nambu-Goldstone boson. In this model the halos are like gigantic atoms, where the ultra-light boson DM particles are condensated in a single macroscopic quantum state ψ . The quantum mechanical uncertainty principle prevents halos from a self-gravitational collapse.

Lee and Koh [14, 12] suggested that this condensated halo DM can be described as a coherent scalar field [15] (dubbed as the boson halo model or, more generally, SFDM model later [16]). On the other hand, in usual CDM models, the wave functions of DM particles do not overlap much and the particles move incoherently. Thus, the key difference between our model and the usual CDM models is the state of DM particles rather than DM itself. Later, similar ideas were suggested by many authors in terms of the fuzzy DM, the fluid DM, or the repulsive DM [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. (See [3] for a review.) Many related models like monopole failing models [34, 35], unstable massless scalar field models [17], and quintessence models [19] are suggested too. There are also extensive literature on, for example, the collision of BEC-dark matter structures [36, 37], non-spherical collapse [38] and virialization processes [38], and the collapse of SFDM fluctuations in an expanding universe [22, 39, 40, 41, 42]. (For a review see [15, 17, 28] and references therein.)

In these models (BEC/SFDM model hereafter) the formation of DM structures smaller than the Compton wavelength ($O(1) pc$) of DM particles is suppressed by the quantum uncertainty principle. (We will see that the actual length scale is somewhat larger.) It was shown that this property could alleviate the problems of the Λ CDM model [23, 25, 43, 44], such as the cusp problem [45] and missing satellite problem. It is also suggested that this model can well explain the observed rotation curves [46], collisions of galaxy clusters [37] and the size evolution of the massive galaxies [47]. Note that the BEC/SFDM particles behave like CDM [48] at the scale larger than galaxies during the cosmological structure formation due to a small velocity dispersion of the Bose-Einstein condensated state. Thus, this model safely satisfies the criteria of the well established structure formation theory above the galactic scales.

In this paper, we show that the minimum mass of galaxies can be explained if DM is in BEC. In Sec. 2 we show the relation between the minimum mass and the minimum length scale of galaxies. In Sec. 3 we review the proposed origin of the minimum length scale in the BEC/SFDM model. In Sec. 4 we present a result of a simple numerical study supporting our theory. Section 5 contains discussion.

2. Minimum mass of galaxies from the minimum length scale

The characteristic length scale ($O(1) \sim O(10^3)$ pc) for the clustering of dark matter is the key feature of the BEC/SFDM [11, 12] and its variants. It is very interesting that this minimum length scale of DM halo seems to be already observed [2]. There are no known stable galaxies with a half-light radius smaller than 120 pc while the maximum size for star clusters deprived of DM is about 30 pc. Furthermore, observational data indicate there is a distinction in phase-space density between a star-cluster and a dwarf galaxy [49]. Since galaxies, especially dwarf galaxies, are highly DM dominated objects, it is plausible that the minimum mass of galaxies observed is connected with DM rather than visible matter in the galaxies. Thus, it is natural to think that the minimum mass of galaxies is somehow related to this finite length scale.

First, let us briefly review the BEC/SFDM model, in which a galactic dark halo is described by a quantum wave function $\psi(r)$ (or scalar field) of the non-linear Schrödinger equation with the Newtonian gravity [11];

$$i\hbar\partial_t\psi = E\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V(r)\psi(r), \quad (2.1)$$

where E is energy of a DM particle and r is the distance from the halo center. The gravitational potential of the halo is given by

$$V(r) = \int_0^r dr' \frac{Gm}{r'^2} \int_0^{r'} dr'' 4\pi r''^2 (\rho_{vis}(r'') + \rho_{DM}(r'')) + V_0, \quad (2.2)$$

where DM density $\rho_{DM}(r) = M_0|\psi(r)|^2$ and ρ_{vis} is the visible matter (i. e., stars and gas) density. M_0 is a mass parameter and V_0 is a constant to make $V(\infty) = 0$. These equations can be also derived in the SFDM theory in the Newtonian limit. For simplicity, we assume there is no self-interaction between the scalar particles except for the gravity.

Let us find the size of a stable configuration of the halo. From Eq. (2.1) the energy E is approximately given by

$$E(\xi) \simeq \frac{\hbar^2}{2m\xi^2} + \int_0^\xi dr' \frac{Gm}{r'^2} \int_0^{r'} dr'' 4\pi r''^2 (\rho_{vis}(r'') + \rho_{DM}(r'')), \quad (2.3)$$

as a function of a halo length scale ξ . A stable ground state configuration of the halo suitable for dwarf galaxies (a zero-node solution) can be approximately found by extremizing the energy by ξ [50];

$$dE(\xi)/d\xi \simeq -\frac{\hbar^2}{m\xi^3} + \frac{GMm}{\xi^2} = 0. \quad (2.4)$$

Here,

$$M \equiv \int_0^\xi dr'' 4\pi r''^2 (\rho_{vis}(r'') + \rho_{DM}(r'')) \quad (2.5)$$

is the total mass within ξ of the galaxy consisting *both* of the DM and the visible matter. The condition in Eq. (2.4) satisfies at [11, 50]

$$\xi = \frac{\hbar^2}{GMm^2} = \frac{c^2\lambda_c^2}{4\pi^2GM}, \quad (2.6)$$

where c is the light velocity and $\lambda_c = 2\pi\hbar/mc$ is the Compton wavelength of the particles. From this equation one can obtain the mass within ξ ,

$$M(\xi) \simeq \frac{\hbar^2}{G\xi m^2}. \quad (2.7)$$

It is well known that, in the BEC/SFDM theory, the size of the stable configuration ξ could not be arbitrary small. Let us denote this minimum value of ξ as ξ_c which is at least λ_c . Then, there appears a minimum mass for the DM halo, $M_c \equiv M(\xi_c) = \hbar^2/G\xi_c m^2$ corresponding to ξ_c . If $\xi_c = \lambda_c \sim 1/m$ and $m \simeq 10^{-24}eV$, the minimum mass for the DM halo becomes $M_c = \hbar c/2\pi Gm \simeq 10^{13}M_\odot$, which is too large for dwarf galaxies. However, note that the free parameter mass $m \sim 10^{-24}eV$ is just one of rough estimates. In the literature on the BEC/SFDM, m was usually suggested to be in the range $O(10^{-26})eV \sim O(10^{-22})eV$ to solve the problems of CDM models.

Conversely, from the observed values of M_c and ξ_c one can obtain approximate mass of DM particles

$$m \simeq \sqrt{\frac{\hbar^2}{G\xi_c M_c}}. \quad (2.8)$$

From the observed value $M_c \simeq 10^7 M_\odot$, one can obtain $m \simeq 5.4 \times 10^{-22} eV$ for $\xi_c = 300 pc$ from Eq. (2.8). For this m , $\lambda_c \simeq 0.075 pc$. (In the next section we will discuss why ξ_c is larger than λ_c .) Very interestingly, this m value is similar to the value $m = 10^{-22}eV \sim 10^{-23}eV$ required to solve the cusp problem and to suppress the small-scale power [22, 26, 51]. Thus, $m \sim 10^{-22}eV$ can solve all known small scale problems mentioned above, which was discussed by Hu, Barkana and Gruzinov in Ref. [22].

3. Minimum length scale of galaxies revisited

In fact, even in the original work [11, 12] it had been already noted that the typical length scale ($O(kpc)$) of galaxies is somewhat larger than the Compton length λ_c . This is related to the fact that the halos are basically non-relativistic objects. ξ_c could be comparable to λ_c only when astronomical objects in consideration are extremely relativistic like black holes. It is clearly not the case for galactic halos. ξ in our equation (2.6) was identified as the gravitational Bohr radius $\sim kpc$ in [11]. In [12] it was argued that de Broglie wavelength λ_{dB} , rather than the Compton length, is more adequate for the typical size of DM structures. (Similarly, in condensed matter BEC systems the coherence length or the healing length, usually comparable to λ_{dB} , rather than λ_c determines the spatial size of BEC density fluctuations [52].)

There are several ways to obtain ξ_c slightly larger than λ_c . The first and most plausible one is the quantum Jeans scale $r_J \sim O((G\rho m^2)^{-1/4})$ [53, 22, 50] for SFDM, which is the geometric mean between the virial dynamical scale and the Compton scale. This scale can be derived from the cosmological evolution equation for the SFDM density perturbation δ with a wave vector k [22, 54]

$$\partial_t^2 \delta + 2H\partial_t \delta - \left(4\pi G\rho - \frac{k^4}{4m^2 a^4}\right) \delta = 0, \quad (3.1)$$

where H is the Hubble parameter, ρ is the mean DM density and a is the scale factor. The second term in the parenthesis represents a contribution from quantum pressure of the DM. The density perturbations are stable below r_J and behave as ordinary CDM above this scale. This fact makes the BEC/SFDM an ideal alternative to the CDM. r_J determines the minimum length scale during the cosmic structure formation, which could be larger than λ_c . (This quantum Jeans instability is also known in the studies of boson stars [55, 56].) According to the standard structure formation theory, a physically meaningful value of r_J can be fixed at the matter-radiation equality having a scale factor $a_{eq} \simeq 1/3200$. At this time $\rho \simeq 3 \times 10^{10} M_\odot a_{eq}^{-3} / Mpc^3$ [57], and the quantum Jeans scale r_J above becomes $O(10^2)pc$ for $m \simeq 10^{-22}eV$. Hence, $\xi_c \simeq r_J$ is plausible. Second, ξ_c can be the coherence length $\sqrt{M_P/\psi_0 \hbar/mc}$ determined by the DM scalar field value ψ_0 at the halo center [20], which might be related to some symmetry breaking. For a simple quadratic potential $\rho \sim m^2 \psi_0^2$, the coherence length again becomes of order r_J [50]. This implies $\psi_0 \sim 10^{-8} M_P$, where M_P is the Planck mass. Third, if there is a self-interaction term $\lambda \phi^4$ between DM particles, a new length scale $\xi_c = O(\lambda^{1/2} \lambda_c M_P/m)$ emerges [17]. Finally, one may also consider a thermal de Broglie wavelength for ξ_c [50]. Thus, ξ_c somewhat larger than λ_c is not new in these models and theoretically possible.

We assume one of these scales plays a role of ξ_c , though the quantum Jeans scale seems to be most plausible for our purpose. Note that all these scales are determined not by the properties of individual halos but by those of the DM particles such as mass, coupling and mean density of the DM particles. Therefore, $\xi_c \simeq O(10^2) pc > \lambda_c$ could be a universal quantity [2]. In short, the nature of the DM particles fixes ξ_c , which in turn decides M_c .

To make a DM dominated structure, the total mass of the structure should be large enough to gravitationally attract DM particles having intrinsic momentum of $O(\hbar/\xi_c)$ due to the uncertainty principle. The critical mass M_c is just the minimum value to do this. From the virial condition, i. e., by equating kinetic energy $((\hbar/\xi_c)^2/2m)$ with potential energy ($V = GMm/\xi_c$), one can check that M_c in Eq. (2.7) is of correct order. It is important to note that, since ξ_c is the property of DM itself, M_c should be independent of the fraction of visible matter, hence the luminosity, as long as the fraction is small. This seems to be the basic physics behind what was observed.

The thermal history of this dark matter is also considered by several authors [58, 50, 59]. Since the dark matter particle is ultra-light, its thermal velocity could be highly relativistic, and some concerns about the BEC transition may arise. There are basically two options. First, BEC/SFDM might simply have been generated by a non-thermal process like axions. Second, even when the DM particles are in thermal equilibrium, contrary to common wisdom, a BEC could form for relativistic bosons [60, 61, 62, 59]. In [59] it is shown that a cosmological BEC always exists for the relativistic SFDM, if $m < 10^{-14}eV$ [60, 61, 62].

After the BEC phase transition at the temperature T_c , almost all DM particles are in a ground state and move coherently rather than randomly. The BEC ground state are favored against thermally excited states owing to the Bose-Einstein statistics of boson particles [50]. According to [59] the present DM number density $n \sim 10^{15}eV^3$ is much larger than the maximum charge density allowed to excited states; $mT_0^2/3 \sim 10^{-30}eV^3$, even when the present temperature of the DM particles is as high as $T_0 \sim 10^{-4}eV$ for

$m \simeq 5.4 \times 10^{-22} \text{ eV}$. (See Eq. (13) of the reference.) Hence, almost all BEC/SFDM particles are in the ground state now even in this case.

Once the relativistic BEC is formed, SFDM particles in the ground state have only a small quantum velocity dispersion $\sim \hbar/m\xi$ and could be bounded in a self-gravitational potential (if $M > M_c$) even though the temperature of the condensate could very high compared to the mass of the particles. The quantum velocity dispersion $\Delta v \sim \hbar/m\xi_c \sim \lambda_c/\xi_c \sim 10^{-4}c \sim O(10)km/s$ is smaller than the escape velocities of dwarf galaxies. For stability analysis, we can think of the boson halos as boson stars [12, 17]. Their stability with respect to various kinds of perturbations or gravitational collapse is shown in many works [16]. All these facts indicate the stability of the dark halos with the BEC/SFDM [63]. There are also universal profiles for boson stars, which are attractors of the collapse of quite arbitrary initial density fluctuations [64].

4. A numerical simulation

To be more concrete, we perform a numerical study using the shooting method [12] for a toy DM halo. Similar numerical work for cases without visible matter has been extensively performed in the studies of boson stars [16]. The dimensionless form of Eq. (2.1) and Eq. (2.2) can be written as

$$\begin{cases} \nabla_{\bar{r}}^2 \bar{V} = (\sigma^2 + \bar{\rho}_{vis}) \\ \nabla_{\bar{r}}^2 \sigma = 2(\bar{V} - \bar{E})\sigma \end{cases} \quad (4.1)$$

Here we have introduced dimensionless quantities [12]

$$\begin{aligned} \sigma &\equiv \sqrt{4\pi G} e^{-i\bar{E}\bar{t}} \psi / c^2, \\ \bar{r} &\equiv mcr/\hbar, \\ \bar{t} &\equiv mc^2 t/\hbar \end{aligned} \quad (4.2)$$

so that all other barred quantities are dimensionless. For example, in this unit, $\bar{\xi} \equiv mc\xi/\hbar$, $\bar{V} \equiv V/c^2$ and $\bar{E} \equiv E/mc^2$.

For visible matter of dwarf galaxies, we use the dimensionless version of the empirical density in Ref. [65]

$$\bar{\rho}_{vis} = 3\beta M_{vis} \left(\frac{\bar{r}}{\bar{r}_c + \bar{r}} \right)^{3\beta} \frac{\bar{r}_c}{4\pi \bar{r}^3 (\bar{r} + \bar{r}_c)}, \quad (4.3)$$

where $\beta = 2$ and M_{vis} is a parameter proportional to the visible matter fraction. It has been shown that this $\bar{\rho}_{vis}$ with the BEC/SFDM can successfully reproduce the observed rotation curves of dwarf galaxies [46]. We choose the visible core size $\bar{r}_c = 664$ corresponding to the physical size $r_c \simeq 40 \text{ pc}$. Considering the observational data, we choose $\bar{\xi}_c = 3985$ ($\xi_c = 300 \text{ pc}$). One can calculate a dimensionless total mass within $\bar{\xi}_c$,

$$\bar{M}_{tot} \equiv \int_0^{\bar{\xi}_c} 4\pi \bar{r}^2 (\sigma(\bar{r})^2 + \bar{\rho}_{vis}(\bar{r})) d\bar{r}, \quad (4.4)$$

which corresponds to a physical mass $M_{tot} = \bar{M}_{tot} M_P^2/m$.

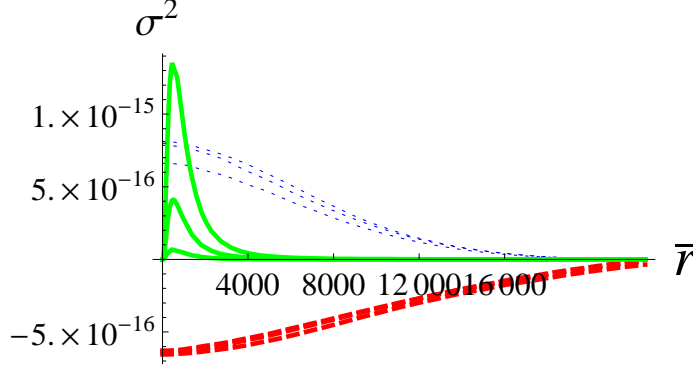


Figure 1: (Color online) The dark matter density σ^2 (blue dotted lines), the visible matter density $\bar{\rho}_{vis}$ (green thick lines) and the gravitational potential \bar{V} (red dashed lines, in units of c^2 , scaled by 3×10^{-8}) for a model dwarf galaxy as functions of distance \bar{r} from the halo center. Despite of wide variations of a visible matter fraction, the 3 profiles have a universal core size $\bar{r}_c = 4000$ (corresponding to the physical size $r_c \simeq 300 pc$) and the total mass within this size $\bar{M}_{tot} \simeq 0.00019$ (corresponding to $4.75 \times 10^7 M_\odot$) is similar for all 3 cases and the gravitational potential functions almost overlap. Here, $\bar{r} = 1$ corresponds to a physical distance $1/m \sim 0.075 pc$ and $\sigma = 1$ to the field value $|\psi| = 1/\sqrt{4\pi G}$.

Fig. 1 shows the result of our numerical study with boundary conditions $d\bar{V}/d\bar{r}(0) = 0$, $\bar{V}(\infty) = 0$ and $d\sigma/d\bar{r}(0) = 0$. For other parameters, we consider 3 cases with the parameters $(M_{vis} = 5 \times 10^{-6}, \sigma(0) = 3.6 \times 10^{-8}, \bar{V}(0) = -2.18 \times 10^{-8}, \bar{E} = -1.7 \times 10^{-9})$, $(M_{vis} = 3 \times 10^{-5}, \sigma(0) = 3.4 \times 10^{-8}, \bar{V}(0) = -2.12 \times 10^{-8}, \bar{E} = -1.3 \times 10^{-9})$, and $(M_{vis} = 1 \times 10^{-4}, \sigma(0) = 2 \times 10^{-8}, \bar{V}(0) = -2.097 \times 10^{-8}, \bar{E} = -1.28 \times 10^{-9})$, respectively, from the top to the bottom for $\sigma(0)$ (reversely for $\bar{\rho}_{vis}$). (One can easily recover the dimensionful quantities by using the transformation in Eq. (4.2) and below. For example, $\bar{E} = -1.7 \times 10^{-9}$ corresponds to the real energy $E = \bar{E}mc^2 = -9.18 \times 10^{-31} eV$.) Three profiles of the potential functions almost overlap as our theory expected. For a similar mass $\bar{M}_{tot} \simeq 0.00019$, the shapes of three $\bar{V}(r)$ are similar, regardless of M_{vis} , as long as DM is dominant. The converse is also true.

The result confirms our arguments below Eq. (2.7). Despite of wide variations of visible matter fraction, the profiles of DM and potential well have a universal core size ($\xi_c \simeq 300 pc$) and the total masses within $300 pc$, $M_{tot} = (0.000189, 0.000190, 0.000189)$, are similar for all 3 cases. (In the physical units these are $M_{tot} \simeq 0.00019 M_P^2/m \simeq 4.75 \times 10^7 M_\odot \simeq M_c$). The masses of the visible matter are $(1.25 \times 10^6, 7.5 \times 10^6, 2.5 \times 10^7) M_\odot$, respectively. Thus, the densities of dark and visible matter are similar to the observed values. In our simulation, what really matter were M_c and ξ_c not the composition of matter within ξ_c . This confirms that there is a universal minimum mass of galaxies composed of the DM and ordinary matter corresponding to the characteristic length scale in the BEC/SFDM theory. This consistency of the theory and observations is non-trivial because the numerical solutions of Eq. (4.1) are very sensitive to the boundary conditions. On the contrary, the results are not sensitive to the form of $\bar{\rho}_{vis}$. We have checked that a similar conclusion can be derived for $\bar{\rho}_{vis}$ with $\beta = 1$. When the DM is subdominant, the universal minimum mass and size

are not shown clearly. This is also expected because the universality is a property of the DM not that of visible matter.

In [64] it is shown that under isolation conditions the rotation curve would be Keplerian, unless an appropriate spatial scale is chosen. We have used the cut-off of the scalar field profile at the boundary $\bar{r} = \bar{r}_0 = 22581$ (corresponding to about 1700 pc) so that the density of the field equals the present average DM density of the universe $\rho_0 \sim 3 \times 10^{10} M_\odot / \text{Mpc}^3$, which corresponds to $\sigma(r_0) \simeq 10^{-11}$ in the dimensionless unit. This is necessary, because the DM density of galaxies is usually non-zero even for large r . With $\psi \sim 10^{-8} M_P$ and $m \sim 10^{-22} \text{ eV}$, we can successfully reproduce the observed halo DM density $m^2 \psi^2 \sim 10^{-4} \text{ eV}^4 \sim 10^7 M_\odot / (100 \text{ pc})^3$ for dwarf galaxies as well as $\xi_c \sim O(10^2 \text{ pc})$. Since above the galactic scale, SFDM basically behaves as CDM [22], we think that the usual bottom-up hierarchical merging process happened for clusters of galaxies.

5. Discussion

We have shown analytically and numerically that the BEC/SFDM theory can explain the three observed properties of dwarf galaxies, i.e., the minimum length scale, the minimum mass scale, and their independence from the brightness. On the other hand, it is difficult to explain all these properties in a *single* scenario in the CDM context, although there are proposed solutions to some of these problems [66, 67] relying on roles of baryon matter. Another merit of our approach is that the stable DM configurations are not much dependent on the complicated galaxy merging history, because the equilibrium condition forces the halos to rearrange their DM distribution so that they have a universal form regardless of their history. This could explain the observed universality of the mass and density profile independent of possible merging history.

In conclusion, the BEC/SFDM could be a compelling alternative to the standard CDM, because it could not only solve some known problems of CDM model such as the cusp problem and the satellite problem, but also has a possibility to explain recent observational mysteries of galaxy evolution in a simple way, thanks to its wave nature and the characteristic length scale. Further tests and future observations may reveal whether CDM is in a BEC.

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